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Experimental study of air cavity thermal performance of opaque ventilated facades under extreme wind conditions: case study Baku

Estudio experimental del rendimiento térmico de la cavidad de aire de fachadas ventiladas opacas en condiciones de viento extremo: estudio de caso Bakú

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ABSTRACT

Widespread use of opaque ventilated facades makes the research of their thermal performance relevant because there is a need for an objective assessment of their energy efficiency at the operational stage. The article is devoted to full-scale experimental research of the thermal characteristics of an air cavity of the naturally ventilated facade system with closed joints under extreme wind conditions by comparing thermal characteristics of air cavity which were based on calculations compliant with construction standards and the full-scale experiment results. Testo 435, 417 were used. An approximate empirical equation was obtained between wind speed when it is more than 7m/s and the cavity air velocity. An increase in wind speed along the wall leads to an increase in cavity air velocity that approaches 1-1.5m/s and a decrease in thermal resistance. Findings can be used for calculated- experimental control of the facade thermal characteristics in order to fulfill a multi-disciplinary energy audit of the building.

Keywords: Opaque ventilated facade; full-scale experimental research; cavity air velocity; wind speed; closed joints; thermal resistance; thermal characteristics.

RESUMEN

El uso generalizado de fachadas opacas ventiladas, hace que la investigación de su rendimiento térmico sea relevante porque existe la necesidad de una evaluación objetiva de su eficiencia energética en la etapa operativa. El artículo está dedicado a la investigación experimental a gran escala de las características térmicas de una cavidad de aire del sistema de fachada ventilada de forma natural con juntas cerradas, bajo condiciones extremas de viento, comparando las características térmicas de la cavidad de aire, se basa en cálculos que cumplen con los estándares de construcción y en los resultados del experimento a escala. Se utilizaron equipos de medición Testo 435 y 417. Se obtuvo una ecuación empírica aproximada entre la velocidad del viento cuando es superior a 7 m/s y la velocidad del aire de la cavidad. Un aumento en la velocidad del viento a lo largo de la pared conduce a un aumento en la velocidad del aire de la cavidad, que se acerca a 1-1.5 m/s y una disminución en la resistencia térmica. Los resultados del cálculo, se pueden usar para el control experimental de las características térmicas de la fachada con el fin de cumplir con una auditoría energética multidisciplinaria del edificio.

Palabras clave: Fachada ventilada opaca; investigación experimental a gran escala; velocidad del aire de la cavidad; velocidad del viento; articulaciones cerradas; resistencia termica; características térmicas.

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1. INTRODUCTION

Today Azerbaijan fully satisfies its internal energy needs with its own resources, but lack of a law on energy-efficiency of buildings slows down the widespread usage of energy-saving and energy-efficient measures in the construction sector (1). According to statistical data, in Azerbaijan, energy consumption by the construction sector accounts for more than 47% of the final energy balance (2). Therefore, one of the ways to improve this situation is to use ventilated facade systems due to their better thermal performance characteristics in comparison to conventional facade systems (3-5). The facades of most buildings in the country do not meet the thermal-technical requirements of existing construction codes and regulations, heat losses through them are significant and make up to 20-28% of the total losses (6,7), therefore additional effective measures are required to insulate the building enclosure. Although the implementation of external insulation of facades is quite a long-term and laborious process the use of ventilated facades systems allows to make new and reconstructed buildings close to energy-saving ones in their thermal characteristics (8-10). Since these systems have significant potential for energy saving, a study of their thermal performance is required, especially during long-term operation in difficult climate conditions, such as significant wind loads and high humidity (11-13), which is typical for climate conditions in Baku, where the referent building is located.

A widespread use of opaque ventilated facades (OVF) makes research of their thermal performance relevant because there is a need for an objective assessment of their energy efficiency at the operational stage. Modern facade systems with ventilated air cavity have become popular subject of science-intensive studies in an overall facade construction (14). At the same time, it is necessary to be aware of the fact that the better a façade deals with all the environmental factors the lower energy demand of the building is (11). There is a significant number of articles that study OVF systems in terms of their energy and thermal performance (11, 15-18). These articles study air cavity in terms of its ability to transfer heat (19-21). There are studies dedicated to experimental measurements of the air velocity in the ventilated cavity (22, 23). Nevertheless, not enough attention has been given to study of naturally ventilated opaque facade systems with closed joints in regions with high wind speed in winter and with low or no solar radiation (24, 25). It is well-known that the wind impact is crucial in determining facade`s thermal performance. Primarily this is due to modern trends in construction such as an increased number of floors in a building. In Baku average wind speed at an altitude of 56 m can be 14 m/s in Baku (1).

Some studies do not take into account the effects of wind on the thermal characteristics of air cavity (19, 26, 27), although wind as a major force of ventilation of air cavity which causes considerable heat losses (11). In addition, the intensity of heat and moisture transfer of OVF depends on the air velocity in the cavity, which is defined by many parameters: internal characteristics of the cavity; number, location, materials, cross-sectional area, thermal conductivity of the fastening elements; aerodynamic resistance in the cavity; external climate influences (28, 29). Therefore, the development methods for calculating cavity thermal performance is a complicated engineering problem (30, 31).

The purpose of this article is to carry out an on-site measurement to assess the air velocity in the ventilated cavity which depends on the height on extended areas of the facade when wind speed is more than 7 [m/s]. Calculations were computed in line with local construction standards and used for further thermal performance study of the cavity. The referent facade is operating. Obtained results are proposed to be applied to calculated-experimental control of OVF for solving practical problems on the operational stage to fulfill the multi-disciplinary energy audit of the buildings and their further certification (32).

2. METHODS

2.1. Specific climate conditions

The thermal properties of the facade are directly linked with the local climate characteristics, this is why it is necessary to take into consideration both the construction object's location and adverse weather conditions (5,19). Design climate conditions for the heating period of the year for Baku are presented in Table 1.

Table 1. Design climate conditions for the heating period of the year.

Name	Symbol	Unit	Value
Average design external temperature		^oC	+5.1
Design internal temperature		^oC	+20
Average fluctuation of temperature during twenty-four hours period		^oC	4-5
Wind speed		m/s	8.4
Heating season from November 15 till April 15		days	119
Prevailing wind direction	-	-	North, North-East
Relative humidity		%	72
Average number of precipitation	-	mm/day	24

In different parts of Baku, macro- and micro-scale climate-forming factors such as wind and radiation, differences in humidity and temperature can be significantly different due to an impact of Caspian Sea, nearby surrounding buildings, existing significant elevation differences and etc.

Azerbaijan is located in the eastern hemisphere at the same latitudes as Spain, Greece, Korea. The capital city is Baku located on the Absheron Peninsula latitude 38 N, longitude 44 E. Here the average annual speed of wind is 6-9 [m/s]. The number of days with speed of wind higher than 15 [m/s] is 100-145 days per year and that number is up to 10-25 days per year for speed higher than 37-42 [m/s].

2.2. Specific facade design solutions

From a design standpoint, there are several types of OVF systems: with open and closed joints between the cladding panels; according to the air inlet and outlet on the top and bottom the cavity types may be closed, semi-open, open (22); naturally and mechanically ventilated. According to the cross-sectional area of the air cavity, it may be: slightly ventilated- ave =500-1500 [mm2] and well ventilated ave≥1500 [mm^2] (33).

Today, in Baku, up to 70-80% of external walls of multi-story buildings are mainly constructed without any thermal insulation due to lack of proper construction legislation (1). They are made out of hollow brick with thermal conductivity coefficient λ=0.52 [W/(m·ºC)], density ρ=1300 [kg/m^3], main masonry thickness d=40 [cm], thermal resistance about R=0.77 [(m^2·ºC)/W] as well as locally produced aerated concrete with λ=0.15 [W/(m·ºC)], ρ=500 [kg/m^3], d=30 [cm], R=2 [(m^2·ºC)/W] is used. In low-rise construction up to three floors in Baku and its suburban areas, the main construction material is local lime stone with λ=0.73 [W/(m·ºC)], ρ=1600 [kg/m^3], d=40 [cm], R=0.55 [(m^2·ºC)/W].

A thermal insulation material that is commonly used is mineral wool slab with a density more than ρ=90 [kg/m3]. The insulation layer thickness is calculated according to SP 50.13330-2012 (Russian acronym, Code of Construction) (34). The insulation layer is mechanically fastened (at least 5 points per 1 [m^2]) or glued on the surface of the main masonry.

Air cavity of OVF, that is ventilated and drained, affects all thermal characteristics of the enclosing structure, and its proper organization is an important practical task (5,19). Per SP 50.13330 (34) the width of air cavity is 40-100 [mm] to provide an upward airflow with air velocity less than 1 [m/s]. Maximum heat-shielding properties of air cavity are achieved with the minimum possible width of the moisture removal (35). The thermal resistance of air cavity depends on wind speed, reflectivity of materials forming air cavity, outside air temperature and solar radiation intensity (36).

As finishing cladding for OVF system, some of the commonly used materials are metal and vinyl siding, ceramic granite, profiled steel sheets, metal cassettes, composite panels, glass with a special coating, high-density laminate, ceramic tiles and so forth.

Finishing cladding can be fixed to the main masonry using fastening elements made of aluminum or steel. As rule, they significantly reduce the total thermal resistance of the wall assembly and make it thermally heterogeneity. In this case, the thermal resistance of the facade is calculated taking into consideration the coefficient of thermal heterogeneity (34-38): for aluminum, for steel .

2.3. Case study

The object of this full-scale experimental study is north orientated facade of the main building of Azerbaijan University of Architecture and Construction (Figure 1). It is located in the most weathered part of Baku amphitheater under prolonged wind conditions. The facade has been operated for more than 11 years.

The main masonry of the facade is a hollow brick on a cement- sand mortar with internal lime-sand plaster. There is also a continuous mineral wool insulation layer. A lightweight cladding of composite smooth panels (height 1.8 [m] and width 0.7; 1; 1.2 [m]) are fastened to the main masonry by steel substructure- steel fastening bolts. The height of the northern facade is 55,8 [m]. Light-colored composite panels absorb approximately 20% of the total amount of solar radiation falling on a vertical surface. Between the insulation layer and cladding panels, there is a slightly- ventilated air cavity with a thickness about 4-7 [cm] which is continuous along the height. A hydro-windproof membrane on the thermal insulation surface is missing.

Figure 1. Case study building: north (measured) facade.

At the base and in the upper part of OVF there are inlet and outlet slots in nearly equal sizes for ventilation of the air cavity. The seal between the facing plates is dense and airtight. The thermal characteristics of the facade layers from internal to external are given in Table 2. Constructive scheme of the cross-section of OVF is illustrated below in Figure 2. In the immediate vicinity of the investigated facade, there are no high-rise buildings which can affect the wind speed.

Measurements of the air velocity in the cavity had been carried out by the multi-function measuring instrument Testo 435 in seven different points through the open joints of the cladding panels. The points have a diameter of about 15 [mm] and they are located along the windward side of the facade oriented to the north. Measurements had been carried out during January and February in the morning and in the afternoon (Figure 1, red dots). Measurements of the wind speed have been carried out at the same height with measuring instrument Testo 417. The average external air temperature was about (2-11) [ºC], the temperature difference between the outside air and the air cavity was about (1-2.5) [ºC]. Data of the average values of measured air velocity and wind speed are given in Table 3.

Table 2. Thermal characteristics of the facade materials.

No	Materials	ρ [kg/m^3]	d [cm]	λ [W/(m·ºC)]	R [(m^2·ºC)/W]
1	Lime- sandplaster	1600	2	0.70	0.029
2	Hollow brick	800	40	0.52	0.77
3	Thermal insulation	150	5	0.044	1.14
4	Steel fastening bolts	7800	-	47	0.1
5	Air cavity	1.25	5	-	0.1
6	Composite panel	-	2.1	-	≈0.06

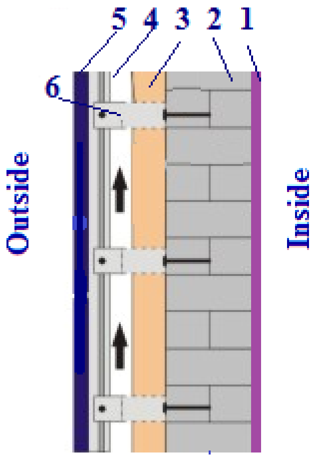

Figure 2. Constructive scheme of vertical cross- section of OVF: 1- internal lime-sand plaster; 2- main masonry; 3- thermal insulation; 4- ventilated air cavity; 5- facing panel; 6- fixing substructure.

Engineering calculations of OVF thermal characteristic values were carried out in accordance with (34, 35). Calculations were made assuming that heat flow through OVF system is stationary, there is structural thermal heterogeneity, as well as solar radiation is lack.

The total thermal resistance to heat transfer of facade is determined by the formula:

[1] $$R_{tot} = R_{si} + R \cdot r_s + R_c + R_p + R_{se}$$

$R_{si}, R, r_s, R_c, R_p, R_{se}$ stand for interior surface thermal resistance, thermal resistance from inner surface to the air cavity, thermal resistance of air cavity, thermal resistance of facing panel, exterior surface thermal resistance, respectively, [(m²·°C)/W], r_s= coefficient of thermal heterogeneity of wall assembly for steel fastening bolts (34-37).

Per (35), in line with ensuring wall energy efficiency, the total thermal resistance, R_T, must be equal or higher than R_{reg}:

[2] $$R_{tot} \geq R_{reg}$$

[3] $$R_{reg} = 0.00035 \cdot D + 1.4$$

where: D number of degree-days of the heating season, [°C·days]:

[4] $$D = (t_{int} - t_{ext}) \cdot z_{ht}$$

where: $t_{int}=20$, t_{ext}=5.1 internal and external temperatures, respectively, [°C];

Z_{ht}=119 number of days with average temperature less than +8 [°C].

For the climate conditions in Baku: D=1773 [°C·days], $R_{reg}=2.02$ [(m²·°C)/W]. According to the calculated results: $(R_{tot}\approx 2.11) \geq (R_{reg}=2.02)$, that means the energy efficiency of the referent wall assembly. Thermal resistance of the air cavity is calculated by formula:

[5] $$R_c = \frac{1}{h}$$

h- heat transfer coefficient of air cavity, [W/(m²·°C)].

Heat transfer in the air cavity occurs due to convection and radiation, so heat transfer coefficient includes two components- convective heat transfer coefficient hh_c, [W/(m²·°C)], and radiative heat transfer coefficient h_r, [W/(m²·°C)]:

[6] $$h=h_c+h_r$$

Varies factors affect the value of convective heat transfer coefficient: cavity geometry, air viscosity, air specific heat and so forth. But it mainly depends on the air velocity in the cavity, V_c [m/s]. Convective heat transfer coefficient is determined by the Frank formula (34, 35, 37):

[7] $$h_c=7.34 \cdot V_c^{0.656}$$

Depending on speed of wind the convective heat transfer coefficient has been broadly investigated by the numbers of scientists and it is shown in (24). Radiative heat transfer coefficient, h_r, [W/(m²·°C)], depends on the intensity of solar radiation and air temperature in the cavity. Radiative heat transfer coefficient equals:

[8] $$h_r = \frac{0.04}{\frac{1}{C_1}+\frac{1}{C_2}-\frac{1}{C_0}} \cdot \left(\frac{t_c+273}{100}\right)^3$$

C_1, C_2, C_0 radiation coefficients of the insulation surface, inside surface of cladding and black-body surface, respectively 4.5, 3.9, 5.76; t_c air temperature in the cavity, it is about (1.5-2.5) [°C] more than exterior temperature for claddings with low thermal conductivity.

The air movement in the cavity occurs under the influence of wind pressure and buoyancy. In general, cavity air velocity should be calculated using the formula below:

[9] $$V_c = \sqrt{\frac{k \cdot V_{10}^2 + 0.08 \cdot L \cdot (t_c - t_{ext})}{\sum_i \varepsilon_i}}$$

V_{10} average speed of wind, [m/s], on the terrain according to the meteorological data on the height $H=10$, [m];

L height difference between the air cavity inlet and outlet, [m];

$\Sigma_i \xi_i$ sum of the local aerodynamic drag coefficients,

ξ=5.5 for input where airflow is bent;

ξ=4.5 for output where airflow is sharply bent;

$(t_c - t_{ext})$ difference between the mean air temperature in the cavity and the mean external temperature that is taken between (1.5-2.5) [°C];

k coefficient of the wind speed change, based on building's height, H, [m] (37):

[10] $$k \approx 0.123 \cdot \sqrt{H}$$

The speed of wind can be calculated based to any building's height, H, more than 10 [m] using the formula (38):

[11] $$V_H = V_{10} \cdot \left(\frac{H}{10}\right)^{\beta}$$

β local terrain exponent, coefficient, that depends on the area type, β=0.4, β=0.28, β=0.16 for urban area with the buildings height H>25[m], H=10–25[m], H<10 [m] respectively, (37).

3. RESULTS

Results of calculated convective heat transfer coefficients and thermal resistances of the air cavity based on the experimental data and engineering equations [1]-[11] are given in Table 3 and Table 4 respectively.

Radiative heat transfer coefficient was calculated by using formula [8] and it is h_r=2.7 [W/(m²·°C)]. It remains constant along the facade height since it depends mainly on the air temperature in the cavity. According to the results of full-scale measurements and formula [6] cavity heat transfer coefficient is: h=10–12.32 [W/(m²·°C)]. Next empirical equation allows to approximate a full-scale experimental values of the cavity air velocity depending on the wind speed according to the façade height:

[12] $$V=0.4\cdot V_f^{0.7}$$

Analysis of experimental and calculated results show that the higher wind speed causes greater cavity air velocity along the facade height (Table 3, 4). Figure 3 illustrates that an increase in cavity air velocity contributes to increases in convective heat transfer.

Table 3. Experimental data of average wind speed, average cavity air velocity, and calculated convective heat transfer coefficient, cavity thermal resistance along the facade's height.

No	L [m]	V_f [m/s]			V_c [m/s]		
1	7.2	7	8	9	1	1,13	1.2
2	14.4	7.8	8.8	10	1.11	1.18	1.26
3	21.6	8.8	10	11.3	1.18	1.26	1.34
4	28.8	9.6	11	12.3	1,2	1.32	1.4
5	36.0	10.2	11.7	13.2	1.3	1.36	1.45
6	43.2	10.8	12.4	13.8	1.3	1.4	1.48
7	46.8	11.1	12.7	14.2	1.33	1.43	1.51

No	L [m]	V_c [W/(m²·°C)]			R_c [(m²·°C) /W]		
1	7.2	7.34	8	8.27	0.1	0.095	0.09
2	14.4	7.7	8.3	8.54	0.092	0.09	0.088
3	21.6	8.18	8.54	8.8	0.09	0.088	0.087
4	28.8	8.3	8.7	9.15	0.088	0.087	0.085
5	36.0	8.72	9	9.2	0.087	0.086	0.084
6	43.2	8.72	9.1	9.49	0.087	0.085	0.082
7	46.8	8.85	9.26	9.62	0.087	0.084	0.08

Table 4. Engineering calculation results based on formulas [5-11].

No	L [m]	V_H [m/s]			V_c [m/s]		
1	7.2	7	8	9	1.39	1.54	1.68
2	14.4	8.1	9.26	10.41	1.55	1.72	1.88
3	21.6	9.53	10.89	12.24	1.76	1.94	2.12
4	28.8	10.69	12.21	13.74	1.91	2.12	2.31
5	36.0	11.68	13.35	15.02	2.05	2.26	2.47
6	43.2	12.57	14.36	16.16	2.16	2.39	2.61
7	46.8	12.98	14.83	16.69	2.21	2.45	2.67

No	L [m]	h_c [W/(m²·°C)]			R_c [(m²·°C) /W]		
1	7.2	9.1	9.74	10.32	0.083	0.078	0.077
2	14.4	10	10.5	11.56	0.078	0.071	0.07
3	21.6	11	11	12.34	0.073	0.072	0.066
4	28.8	11.22	12	13	0.07	0.067	0.063
5	36.0	11.77	12.5	13.56	0.068	0.065	0.061
6	43.2	12	13	13.8	0.066	0.064	0.06
7	46.8	12.34	13.2	14	0.065	0.63	0.06

Figure 4 shows that the measured thermal resistance of the cavity decreases with height and does not exceed 0.1 [(m²·°C)/W]. In the middle part of the cavity between 14–36 [m] of height, thermal resistance has a smaller gradient of change, unlike zones next to the air inlet and outlet openings, which demonstrates the influence of openings on change in the thermal resistance of the cavity.

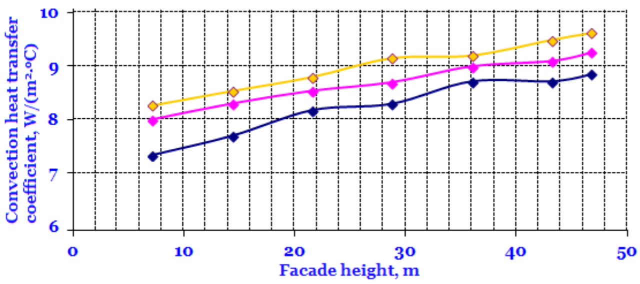

Figure 3. Convective heat transfer coefficient, h_c, in the air cavity based on experimental data, Table 3: for V_{10} = 7 [m/s], for V_{10} = 8 [m/s], for V_{10} = 9 [m/s].

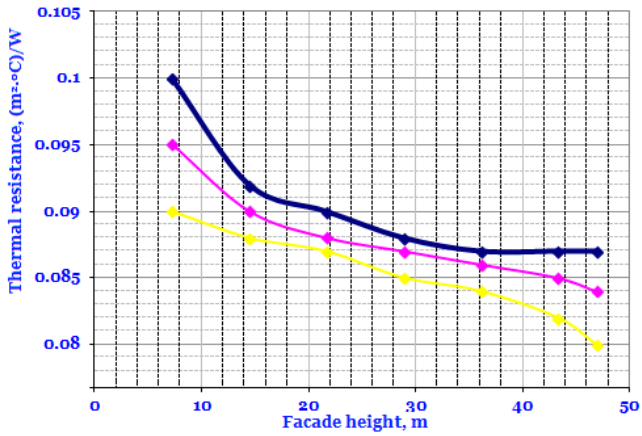

Figure 4. Cavity thermal resistance, R_c based on experimental data, Table 3: for V_{10} = 7 [m/s], for V_{10} = 8 [m/s], for V_{10} = 9 [m/s].

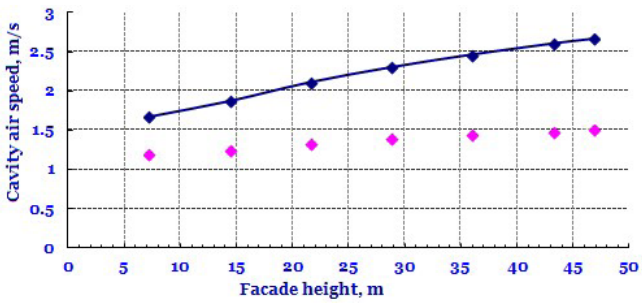

Figure 5. Cavity air velocity results, V_c, based on: experimental data, Table 3, calculated data, Table 4

4. DISCUSSIONS

The purpose of this article was to study the thermal characteristics of an air cavity of a naturally ventilated facade system with closed joints under extreme wind conditions in the winter period. The study compared thermal characteristics of the air cavity which were based on calculations compliant with the construction standards on the base of the full-scale experiment.

The results of the full-scale experiment on measuring cavity air velocity and wind speed and subsequent engineering calculations allow us to perform a more accurate calculation on the thermal parameters of the air cavity: convective heat transfer coefficient and thermal resistance. The study has shown that the results obtained based on experimental data are approximately the same as the ones based on engineering-calculation. The more accurate match cannot be expected because of the many random factors that can influence the results of the experiment.

Analysis of the results of the full-scale experimental study on the thermal performance of the air cavity of ventilated façade with the height up to 60 m under the speed of wind more than 7 [m/s] shows that:

1. the real thermal condition in the air cavity differs from the theoretical studies, which do not take into consideration the areas of inlet and outlet openings for ventilation of the cavity, as well as fastening system of the external cladding panels. The substructure of the panels, sited in the cavity, significantly influence the value of the hydraulic resistance to air movement in the cavity (38);
2. an increase of wind speed along the facade's height leads to an increase in cavity air velocity which can be 1-1.5 [m/s]. This causes a decline of the cavity thermal resistance;
3. the resulting approximate equation [12] more accurately reflects actual air velocity in the cavity. It allows to calculate cavity air velocity which depends on wind speed and can be used for shortened calculation;
4. although the construction codes indicate that the heat transfer coefficient should be constant (34, 35), the results of the full-scale studies show that this parameter varies. That is why it is necessary to calculate the heat transfer coefficient of the air cavity for each particular facade during the cold period of the year. According to the results of field measurements the cavity heat transfer coefficient is 10-12.32 [W/($m^2 \cdot {}^oC$)], where convective heat transfer accounts for about 75%, and radiative heat transfer coefficient accounts for about 25%. This indicates that the value of the convective heat transfer coefficient is three times greater than the value of the radiative heat transfer coefficient. This is due to significant wind impact on the outer surface of OVF. Since an increase in wind speed causes changes in the air movement characteristics, the heat exchange between the air and the cavity inside surfaces is also changing (39).
5. the findings show that the experimental values of air thermal resistance are consistent with the results (11) due to the existence of a "static air layer" at 14–36 [m] height. This proves that the cavity end parts are cooler compared to the middle part, which indicates greater heat losses at the end parts.

Results that were concluded in this article are consistent with the ones in the studies referenced and cited in these articles (5, 19, 22, 38). This confirms the reliability and reasonableness of the results.

5. CONCLUSIONS

In Baku, the enclosure structures of building operate in fairly hard operation mode, experiencing the effects of constant strong wind, significant humidity and temperature drops (1). Therefore, in order to decrease energy demand in buildings and avoid deformation and damage, it is very important that materials, combined into a common structure, would be investigated for long-term functionality and reliability during their operational stage (14). The findings of the conducted full-scale experiment confirm the necessity of a comprehensive experimental-numerical solution for the structures of ventilated facades.

Since the cavity influences significantly the thermal properties of OVF, this should be considered when calculating the energy efficiency of buildings (5, 25). Consideration of the impact of wind speed on the cavity thermal regime only improves the accuracy of thermal calculations and corrects them. Some of the practical applications, based on the results of this full-scale experimental study of the thermal characteristics of air cavity on a ventilated facade under significant wind effects can be applied when calculating temperature distribution over the cavity`s height, the intensity of moisture transfer and heat transfer along the facade. Obtained results complement calculated-experimental control of heat and energy indicators of the building during when carrying out its energy audit and further certification. The results of field studies show that for using OVF in conditions with strong wind effects it is necessary to improve and develop the existing calculating methods. This will result in increased functional characteristics, operational reliability as well as durability of OVF.

In Azerbaijan, application of OVF is growing rapidly. As such they contribute to an increase in energy efficiency of buildings. It is important that local specialists continue improving the methodology of complete and accurate thermal engineering calculation of OVF based on the national standards, combined with the full-scale experiments and theoretical studies. Thus, by applying of the results of field measurements in combination with calculations based on the use of standard indicators solves the problem of determining the actual heat- engineering characteristics of external enclosing structures of buildings in actual conditions of their operation. This article does not claim a complete solution to the problem to study the thermal performance of air cavity of OVF. This study was limited by air cavity thickness and values of wind speed. The authors are confident that the search for optimal methods to calculate the thermal performance of OVF is necessary and will be further developed.

Note

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